Optica Applicata, Vol. XXIII, No. 1, 1993

Noise equivalent temperature difference of infrared systems under field conditions

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The noise equivalent temperature difference (NETD) is one of the most convenient measures used for describing performance of infrared systems as thermographs and radiometers. The NETD expression is also contained as a kernel within any minimum resolvable temperature (MRT) and minimum detectable temperature (MDT) difference, so the conclusions to be reached relative to NETD apply to MRT and MDT as well. For the reason of convenience, some assumptions have been made in defining (measuring and deriving relation for) the NETD. However, for a variety of practical purposes in the field these assumptions are not satisfied. Consequently, the conventional laboratory NETD is applicable under certain favourable laboratory conditions. Therefore, the typical laboratory NETD expressions found in the literature cannot be simply applied to infrared systems under field conditions. In this paper, the practical field NETD expression is derived. It incorporates none of the assumptions which have been used in defining and deriving the laboratory NETD expression. Therefore, the given expression can be simply applied to assessment of infrared systems capability under field conditions.

1. Introduction

The noise equivalent temperature difference (NETD) has been defined as the temperature difference (TD) between an extended source (the image of it should be a few times greater than one detector element) and the background, giving rise to a peak signal to noise ratio (SNR) equal to unity at the output of the detector

$$\mathrm{NETD} = \mathrm{TD} \quad \text{when} \quad \mathrm{SNR(TD)} = 1. \tag{1}$$

For reason of convenience, at least four assumptions have been made in defining (measuring and deriving relation for) the NETD:

i) the temperature differences (TD) between the target and the background are small ($< 1°C$),

ii) background spectral characteristic is the same as the target one,

iii) the atmospheric transmittance is equal to unity,

iv) the work conditions of the infrared detector (the effective temperature of background and detector field of view) are the same as the conditions for which the available detectivity was measured.

Consequently, the conventional laboratory NETD is applicable under certain favourable laboratory conditions.

For a variety of practical purposes in the field, however, atmospheric transmittance is low, large temperature differences occur in thermal scenery targets spectral characteristics are different than background ones; the work conditions of the infrared detector are different than the conditions for which the available detectivity was measured. Therefore the typical laboratory NETD expressions found in the literature cannot be simply applied to infrared systems under field conditions.

The assumptions mentioned above can be eliminated by:

– introduction of more general field NETD definition,

– derivation of the practical field NETD expression,

– derivation of the relationship between the field detectivity value of the infrared detector and the laboratory one.

Let us define the practical field NETD as a relation of the temperature difference between an extended source (the target) and the background to the signal to noise ratio (SNR) at the output of the detector which has been caused by this temperature difference, under practical field conditions

$$\mathrm{NETD}_f = \frac{T_t - T_b}{\mathrm{SNR}(T_t, T_b)} \tag{2}$$

where T_t and T_b are the target and local background temperatures.

2. Derivation of the field NETD

When imaging two objects having temperatures T_b and $T_t = T_b + \mathrm{TD}$, the signal to noise ratio at the output of the detector is [1]

$$\mathrm{SNR} = \frac{\pi\tau_o D_f^*(AN)^{1/2}}{4F^2(\Delta f)^{1/2}} \Delta L^*(T_t, T_b) \tag{3}$$

where: τ_0 is the effective optical transmittance, A is the detector area, F is the F-number of the imaging optics, N is the number of detectors scanned and/or summed in series, D_f^* is the maximum field density of IR detector and $\Delta L^*(T_t, T_b)$ is the apparent effective radiance difference.

The $\Delta L^*(T_t, T_b)$ is given by

$$\Delta L^*(T_t, T_b) = \int [L(T_t, \lambda) - L(T_b, \lambda)] g(\lambda) \tau_a(\lambda, \mathrm{WEC}, R) f(\lambda) d\lambda \tag{4}$$

where: λ is the wavelength, $\tau_a(\lambda, \mathrm{WEC}, R)$ is the atmosphere spectral transmittance dependent on wavelength λ, the distance R and weather conditions (WEC), $g(\lambda)$ is the relative wavelength response of the detector, and $f(\lambda)$ represents the spectral distributoin of an appropriate filter. The practical field NETD relation can be obtained by introducing Eq. (3) into Eq. (2), and we get

$$\mathrm{NETD}_f = \frac{4F^2(T_t - T_b)(\Delta \mathrm{f})^{1/2}}{\pi\tau_0 D_f^*(AN)^{1/2} \Delta L^*(T_t, T_b)}. \tag{5}$$

After using Equation (4), we have

$$\mathrm{NETD}_f = \frac{4F^2(T_t - T_b)(\Delta f)^{1/2}}{\pi\tau_o D_f^*(AN)^{1/2} \int [L(T_t, \lambda) - L(T_b, \lambda)] \tau_a(\lambda, \mathrm{WEC}, R) g(\lambda) f(\lambda) d\lambda}. \tag{6}$$

To calculate the NETD_f from Equation (6), the practical field detectivity value D^*_f (not the easily available laboratory one) of the IR detector is required. As this cannot be taken from typical catalogue data found in the literature it can be derived in a way described below.

3. Derivation of the field infrared detector detectivity

The background radiation received by IR photodetector is a composite of the thermal radiation not only from background in the vicinity of the target, but also from the atmosphere between the target and the infrared system and from the optical and scanning systems. The radiation can be characterized by a single blackbody [2]. Let us call the temperature of the blackbody as the effective temperature of the local background T_b.

The detectivity D^* of infrared detectors strongly depends on background radiation received by the IR detector. Therefore, the detectivity D^* strongly depends on the two independent values:

– the detector field of view Ω (solid angle determined by the detector field shield),

– the effective temperature of the local background T_b.

The detectivity values found in the literature are measured in laboratory conditions for the laboratory values of the parameters mentioned above. However, the practical field values are usually different from the laboratory ones. Therefore, the practical field detectivity is usually different from the laboratory one.

Let us find the relationship between the values mentioned above. The components of the infrared detector noise current i_n are [3]:

$$i_n = [(\text{generation-recombination noise resulting from incoming photons})^2 + (\text{generation-recombination noise resulting from thermally-generated carriers})^2 + (\text{Johnson-Nyquist noise})^2 + (1/f \text{ or flicker noise})^2]^{1/2}. \tag{7}$$

The components of the infrared detector noise current i_n can be divided into two groups (external i_{ext} and internal i_{int})

$$i_n = [(i_{ext})^2 + (i_{int})^2]^{1/2} \tag{8}$$

where the external group includes generation-recombination noise resulting from incoming photons; the internal group includes the other components.

For the case of background-limited performance (BLIP) detector the internal noise components disappear, and we have

$$(i_n)_{BLIP} = i_{ext}. \tag{9}$$

It is known that the detector detectivity is inversely proportional to the noise current. Therefore, it can be written:

$$D^* \approx [(i_{ext})^2 + (i_{int})^2]^{-1/2},$$

$$D^*_{\mathrm{BLIP}} \approx [i_{\mathrm{ext}}]^{-1}. \tag{10}$$

The internal noise current is independent of the incoming radiation. This means that it is independent of the detector field of view. Instead, the external noise current is proportional to square root of the incoming radiation. For that reason, under laboratory conditions the external noise current is proportional to square root of the internal one of the effective irradiance of the detector. The effective irradiance is the product of the irradiance of the detector and the relative wavelength response of the detector $g(\lambda)$. Similarly, the external noise current in field conditions is proportional to square root of the internal one of the effective irradiance of the detector under those conditions. Therefore it can be written:

$$i^l_{\mathrm{ext}} \approx [\int E_l(\lambda)g(\lambda)d\lambda]^{1/2},$$
$$i^f_{\mathrm{ext}} \approx [\int E_f(\lambda)g(\lambda)d\lambda]^{1/2}. \tag{11}$$

where E_l is the irradiance under laboratory conditions, and E_f – in field ones.

The relationships (10) and (11) lead us to the following system of equations:

$$\begin{cases} \dfrac{D^{*l}_{\mathrm{BLIP}}}{D^*_l} = \dfrac{[(i^l_{\mathrm{ext}})^2+(i_{\mathrm{int}})^2]^{1/2}}{i^l_{\mathrm{ext}}}, \\ \dfrac{D^{*f}_{\mathrm{BLIP}}}{D^*_f} = \dfrac{[(i^f_{\mathrm{ext}})^2+(i_{\mathrm{int}})^2]^{1/2}}{i^f_{\mathrm{ext}}}, \\ \dfrac{i^f_{\mathrm{ext}}}{i^l_{\mathrm{ext}}} = 1/n, \\ \dfrac{D^{*f}_{\mathrm{BLIP}}}{D^{*l}_{\mathrm{BLIP}}} = n, \end{cases}$$

$$n = \left[\frac{\int_0^\infty E_l(\lambda)g(\lambda)d\lambda}{\int_0^\infty E_f(\lambda)g(\lambda)d\lambda}\right]^{1/2}. \tag{12}$$

The solution of the system of Equations (12) is the relationship

$$D^*_f = \frac{nD^{*l}_{\mathrm{BLIP}}}{[n^2[D^{*l}_{\mathrm{BLIP}}/D^*_l - 1]+1]^{1/2}}. \tag{13}$$

The values of the detectivity in laboratory conditions D^*_l and D^{*l}_{BLIP} can be simply taken from the literature.

To calculate D^*_f from Equation (13), we have to determine the values of the irradiance of the detector under laboratory and field conditions.

The irradiance of the detector under laboratory conditions E_l is

$$E_l(\lambda) = \{L(T_b,\lambda)+[L(T_0,\lambda)(1-\tau_o(\lambda))]\}\tau_o(\lambda)f(\lambda)\Omega_l \tag{14}$$

where T_b, T_0 are temperatures of the background and the optics; and Ω_l is the detector field of view under laboratory conditions. The irradiance of the detector under field conditions E_f is

$$E_f(\lambda) = \tau_o(\lambda)f(\lambda)\{\tau_a(\lambda)[L(T_t,\lambda)\Omega_t + L(T_b,\lambda)(\Omega_f - \Omega_t)] + A\},$$
$$A = [L(T_a,\lambda)(1-\tau_a(\lambda)) + L(T_0,\lambda)(1-\tau_o(\lambda))] \quad (15)$$

where Ω_f is the detector field of view (solid angle subtended by cold shield) in field conditions and Ω_t is target angular subtense.

The ideal cooling shielding is considered to be the case where the cold shield acceptance angle equals the angle subtended by the exit cone of the optical system. For circularly symmetric optical system, the usual case, the detector field of

$$\Omega_f = \pi/(2F)^2. \quad (16)$$

As it is shown, the practical field detectivity D_f^* depends on many different factors, such as: the temperature of the target, the background, atmosphere and optics; on the optics F-number, target angular subtense, atmosphere transmittance, optics transmittance, spectral distribution of the filter and relative wavelength response of the detector $g(\lambda)$, and may be different from that obtained in laboratory, D_l^*.

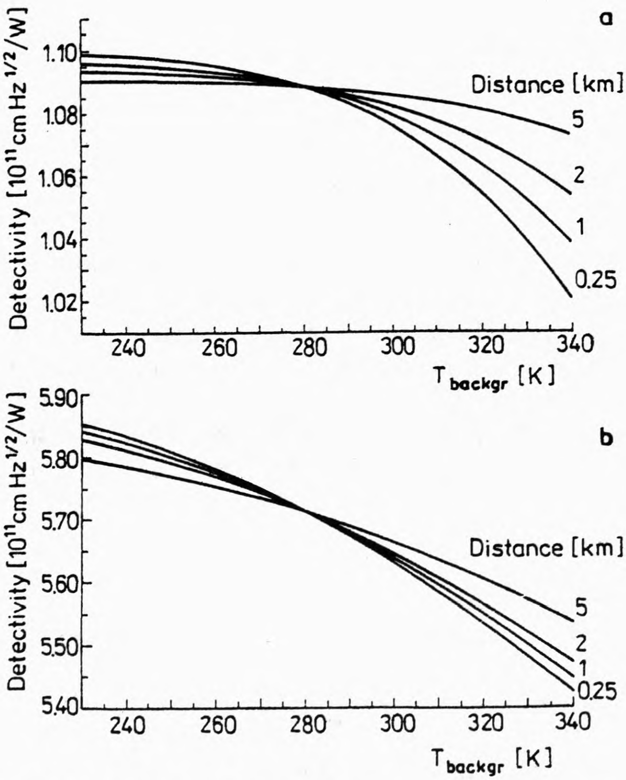

Fig. 1. Field detectivity of infrared detectors of: **a** — 3–5 μm range, **b** — 8–12 μm range in typical field conditions (atmosphere temperature 280 K)

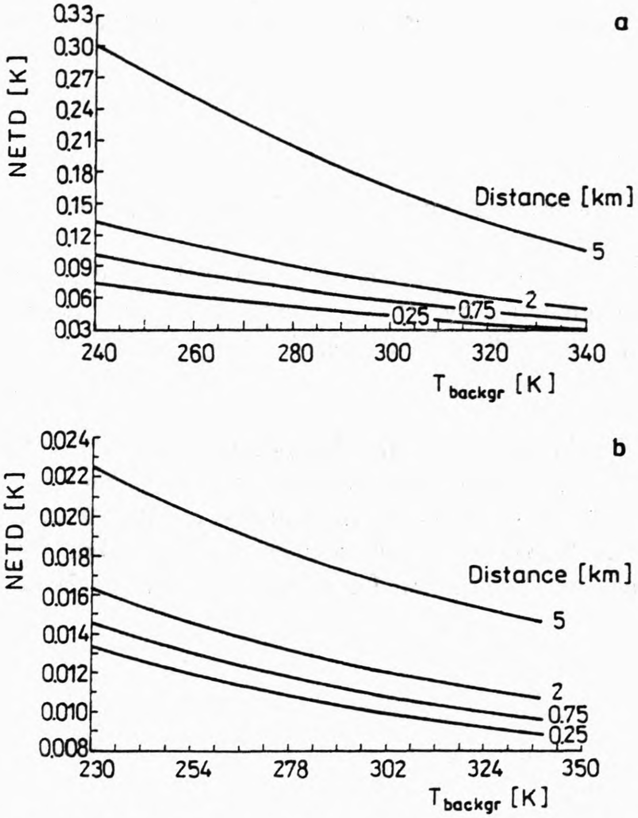

Fig. 2. Field NETD of typical infrared sensor of: a — 3–5 μm range, b — 8–12 μm range in field conditions

The strong dependence of detector detectivity on its field of view is well known. But from Eq. (13) it is possible to determine also the dependence of detector detectivity on field scene parameters (target, background, atmosphere temperature). The dependence is not as strong as for the case mentioned above, but sometimes may be quite significant (Fig. 1).

Now the practical field detectivity D^*_f is known and we can determine the practical field NETD from Eq. (6), Fig. 2. The calculations have been made for the parameters presented in the Table.

Table. Sensor, target, background, atmosphere parameters

Waveband	3–5 μm	8–12 μm
Detector	InSb	HgCdTe
Detectivity	2.65×10^{10} [cm Hz$^{1/2}$/W]	1.63×10^{10} [cm Hz$^{1/2}$/W]
Reference angle	90°	30°
BLIP detectivity	10.2×10^{10} [cmHz$^{1/2}$/W]	5.6×10^{10} [cmHz$^{1/2}$/W]
Detector area	50 × 50 μm	50 × 50 μm
Target temperature	345 K	345 K

Table, continued

Atmosphere temperature	280 K	280 K
Number of elements	10	10
Noise equivalent bandwidth	100 kHz	100 kHz
Optics F-number	2	2
Optics temperature	300 K	300 K

4. Laboratory NETD

When the temperature differences (TD) between the target and the background are sufficiently small, atmospheric transmittance is unity and we may write

$$\lim_{\mathrm{TD}\to 0} \Delta L(T_t, T_b) \simeq \mathrm{TD}\frac{\delta}{\delta T}. \tag{17}$$

If the work conditions of the infrared detector are the same as the conditions for which the available detectivity was measured, we get

$$D^*_f = D^*_l. \tag{18}$$

Temperature difference obtained by introducing the due expressions from (17) and (18) into Eqs. (3) and (4), and equating signal and noise by putting the SNR = 1, is the classically defined and quoted laboratory NETD

$$\mathrm{NETD}_l = \frac{4F^2(\Delta f)^{1/2}}{\pi\tau_o D^*_l(AN)^{1/2}\int L'(T_b,\lambda)g(\lambda)d\lambda} \tag{19}$$

where $L'(T_b,\lambda)$ is the derivative of the spectral radiance with the temperature at the radiation wavelength λ and background temperature T_b.

5. Conclusions

The classical laboratory NETD is the particular case of the more general field NETD. Equations (6), (13) for the field NETD incorporate none of the assumptions which have been used in defining and deriving the laboratory NETD expression (19). Therefore, practical field NETD can be simply applied to assessment of the infrared systems capability under field conditions. Also practical field specific detectivity D^*_f can be applied to assessment of infrared detector capability under those conditions.

References

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Received July 5, 1993